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RAW MATERIALS AND EQUIPMENT WERE OBTAINED AND NEW HIGH TEMPERATURE SUPERCONDUCTORS (HTSC'S) WERE FABRICATED. YBCO MATERIAL SHOWED PROMISING RESPONSE TO A 1T ELECTROMAGNETIC FIELD. THREE METHODS OF QUENCHING SUPERCONDUCTIVITY EXAMINED. FOUR-POINT MEASUREMENT TECHNIQUE USED. HTSC SAMPLES WERE LONG BARS OF BULK MATERIAL WITH SILVER CONTACTS, YBaSaCaO MATERIAL HAS 200 TIMES HIGHER NORMAL STATE RESISTIVITY THAN YBCO, BUT LOW CURRENT DENSITY. PULSED CURRENT QUENCHING EXPERIMENT CAUSED SAMPLE TO QUENCH IMMEDIATELY, BUT TOOK SEVERAL MSEC TO RECOVER. MAGNET PULSE CIRCUIT AND MICROWAVE EXPERIMENTS SET UP. MAGNETIC QUENCHING APPROACH PROVIDES A FAST OPERATION (~~≤10 MICROSEC~~) OF THE SWITCH BUT REQUIRES CIRCUITS FOR GENERATING FAST MAGNETIC PULSES. MICROWAVE QUENCHING WAS MAINLY A THERMAL PROCESS AND THUS WAS SLOW. CONCLUSION: FEASIBILITY DEMONSTRATED.

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Final Report

for

Feasibility Study of High Tc Superconductor Opening Switches

(March 15, 1988 - September 30, 1988)

Submitted to

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I. Introduction

Studies have been conducted to explore the feasibility and characteristics of high Tc superconductor opening switches. The following three controlling mechanisms are applied to the opening of the switch for the current to flow through the load: (i) magnetic quenching, (ii) microwave quenching, and (iii) pulsed current quenching. Ceramic superconductor $YBa_2Cu_3O_{7-x}$ is used as the material for fabricating the test switches. In the following three sections, each of these three modes of high Tc superconductor opening switches will be discussed. Finally, conclusions will be given in the section V.

II. Magnetically Controlled High Tc Superconductor Opening Switch

A jitter free, repetitive opening switch made of $YBa_2Cu_3O_{7-x}$ high temperature superconductor is demonstrated. The switch conducts electrical current at no loss when it is superconducting. A pulse or pulse train of magnetic field on the order of 100 Gauss causes the transition of the switch from the superconducting state to the resistive normal state and forces current to flow through a load resistor that is connected in parallel with the switch. Repetitive operation of this switch at rep-rate higher than 1 kHz has been demonstrated.

The discovery of superconductors with superconductivity transition temperatures above liquid nitrogen temperature[1] has stimulated a great deal of interest in the development of applications based on these new classes of materials. In the

power applications of the high temperature superconductors (HTSC), the zero resistance of the HTSC is used for power transmission or energy storage. For these applications, high performance electrical contacts and switches are desirable. We have reported various high performance electrical contact techniques for HTSC applications [2-4]. In this work we study HTSC switches and demonstrate the jitter free, repetitive switching of electrical current from the HTSC switch to a load by means of magnetic triggering. An HTSC switch made of $YBa_2Cu_3O_{7-x}$ is schematically shown in Fig. 1. Rectangular bars of $YBa_2Cu_3O_{7-x}$ are prepared by (a) mixing $BaCO_3$, Y_2O_3, and CuO, (b) repeatedly (three times) grinding and sintering at 935 C for 16 hours in oxygen atmosphere, (c) pressing at a pressure of 10,000 kg/cm^2 into the rectangular shape of 5mm wide and 75 mm long with thickness between 0.5 and 2 mm, (d) sintering at 950 C for 6 hours in oxygen atmosphere, and (e) cooling slowly in the furnace to 400 C and staying at this temperature for 4 hours. HTSC prepared by this process has the superconductivity critical current density around 160 A/cm^2 at 77K and zero magnetic field according to the 1uV/cm standard. Silver contacts are made on these HTSC bars by means of silver evaporation[2], molten silver processing[3], or heat treated silver painting technique[4]. Copper wires are soldered to the silver contacts and arranged to minimize the interference caused by the magnetic pulse, i.e. to minimize the circuit loop that is exposed to the magnetic field. The finished HTSC is protected by acrylic spray coating.

Shown in Fig. 2(a) is the circuit diagram for the HTSC opening switch circuit with the switch immersed in liquid nitrogen. The current source supplies a current equal or less

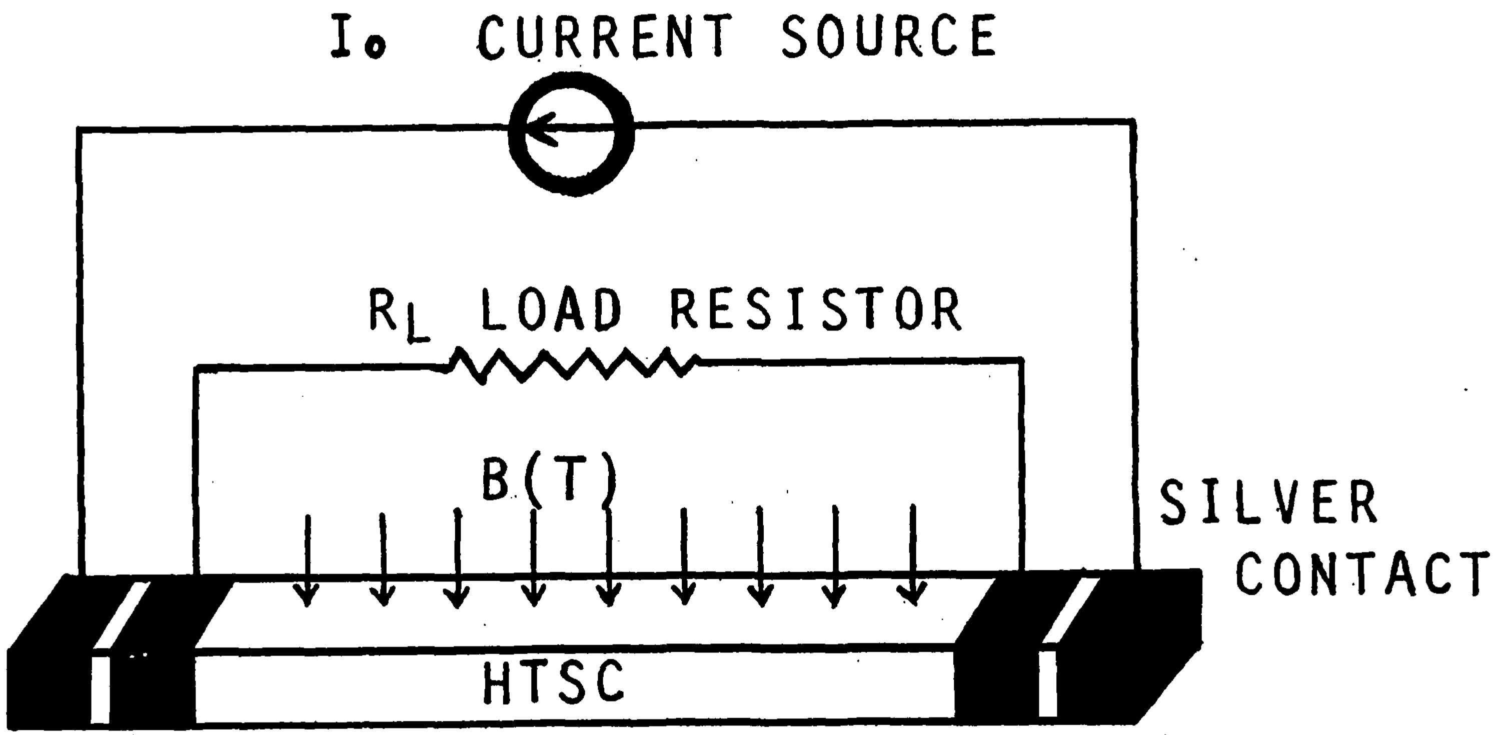

Fig. 1. Schematic diagram of a superconductor opening switch system.

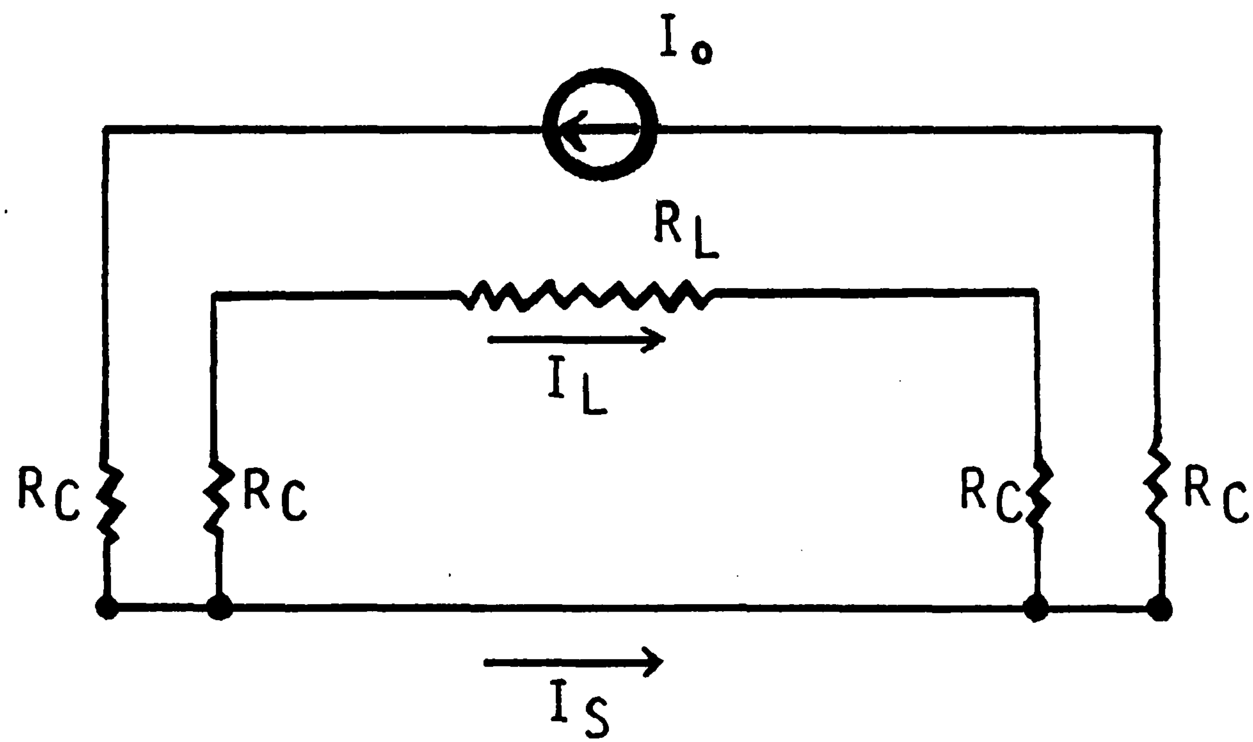

Fig. 2a: Circuit diagram representing a high Tc superconductor opening switch at zero magnetic field and the temperature of liquid nitrogen. I_o is the current supplied by a current source. R_L is the load resistor. R_C is the metal-superconductor contact resistance. I_L is the current flowing through the load resistor. I_S is the current flowing through the central section of the superconductor switch.

than the critical current of the HTSC switch to the outer two contacts on the switch. A low resistance, on the order of a few mohm, load is connected between the inner two contacts. Without an applied magnetic field, the switch is superconducting and all the current from the current source flows through the switch with load current, I_L equal to zero. When a magnetic field of tens of gauss is applied, in a direction perpendicular to the current flow, to the central section of the superconductor bar between those two inner contacts, the HTSC that is exposed to the applied magnetic field becomes resistive as shown in Fig. 2(b). The amount of current that can be switched to the load is determined by the current divider rule based on the resistance of the HTSC and the load as well as silver contacts.

When a magnetic field is applied, the critical current of the HTSC switch decreases significantly with increasing magnetic field up to about 100 gauss and then decreases slowly with magnetic field. The I-V characteristics of an HTSC switch with critical current equal to 8.4 amperes is shown in Fig.3 as a function of the applied magnetic field. The horizontal axis is the current flowing through the central section of the HTSC switch and the vertical axis is the voltage drop across the same section of the HTSC switch that is measured without connecting a load. As the magnetic field increases, the I-V curve shifts to the left at a rate that increases with magnetic field between 0 and 20 gauss and decreases with magnetic field between 20 and 100 gauss. For magnetic field between 100 and 200 gauss, that is the highest magnetic field tested in this work, the I-V curve stays about the same. The dependence of ceramic HTSC current density on magnetic field may be attributed to the "weak

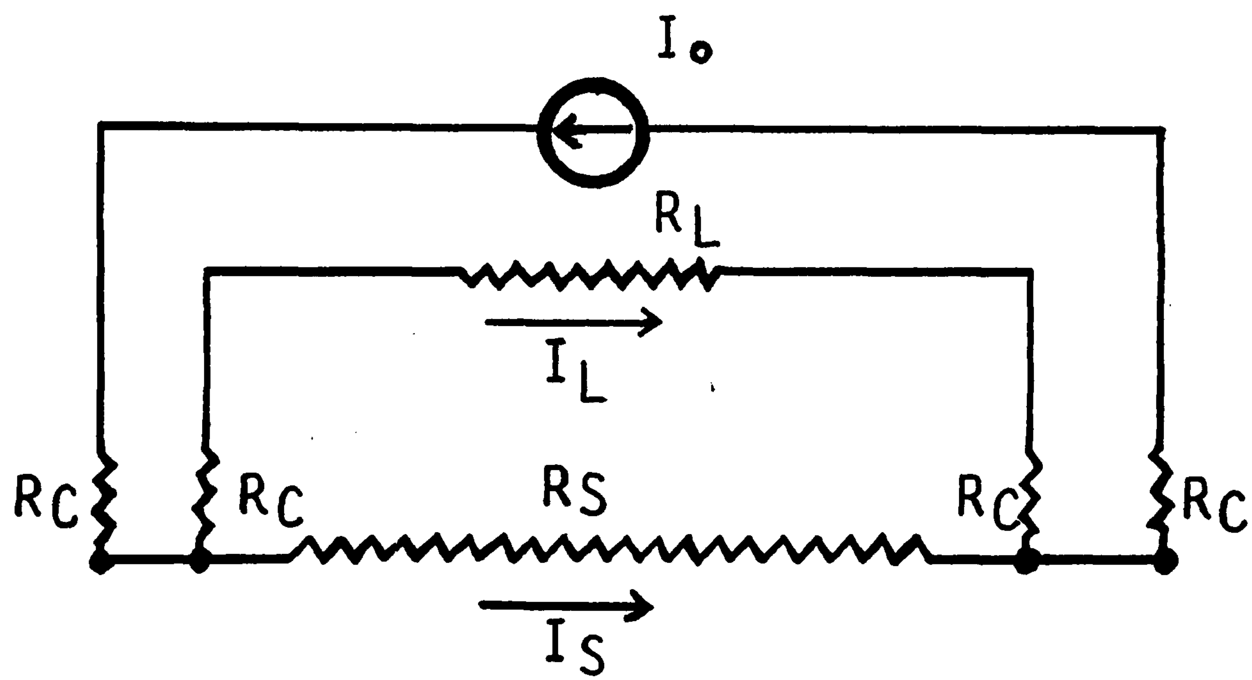

Fig. 2b. Circuit diagram representing a high Tc superconductor switch in a magnetic field. R_S is the resistance of the central section of the switch that has been affected by the applied magnetic field.

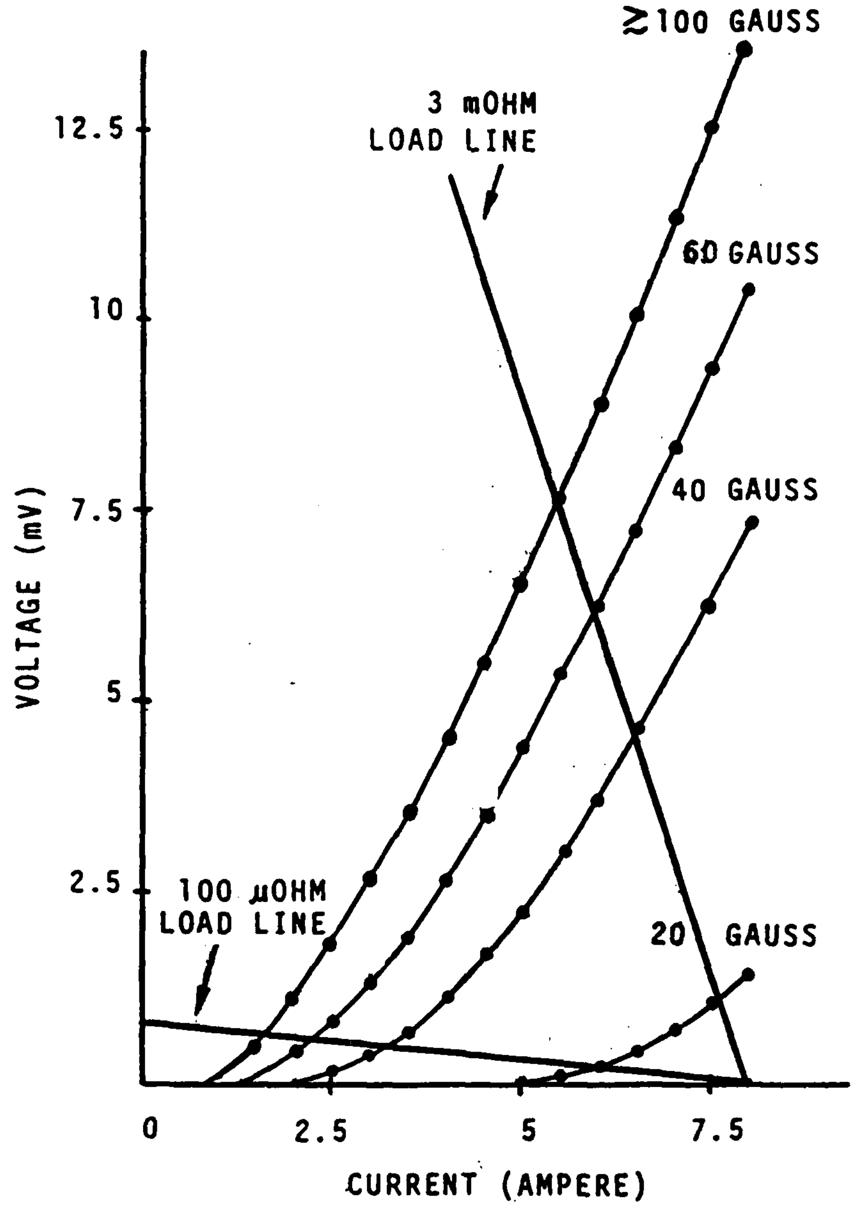

Fig. 3. Current-voltage characteristics of a high Tc superconductor switch. Two load lines corresponding to 3 mohm and 100 uohm respectively are also shown. The maximum magnetic field tested is 200 gauss.

coupling" effect between superconducting grains[5,6] in the HTSC bar and therefore is dependent upon the sample preparation process. The operation of the HTSC switch can be interpreted in aid of a load line representing the I-V characteristics of the load resistor as well as the contact resistance between the load and the switch. For high performance silver contacts with the contact area larger than the crossectional area of the HTSC bar, the contact resistance, R_C, is less than one micro-ohm and can be neglected in this case. Therefore, the load line is a straight line represented by the equation

$$I_o = I_S + V_S/R_L \tag{1}$$

where I_o is the current supplied by the current source; I_S is the current flowing through the central section of the HTSC bar between the inner two contacts; V_S is the voltage across the HTSC between the inner contacts; R_L is the load resistance.

Two load lines corresponding to 8 amperes power supply current and 3 mohm and 0.1 mohm load resistance respectively are shown in Fig. 3 in conjunction with the I-V curves for the 8.4-ampere HTSC switch. The intersection between a load line and the I-V curve corresponding to the maximum applied magnetic field determines the division of the current from the current source between the load and the central section of the HTSC bar. As shown in Fig.3 ~~Fig. 4,~~ for the HTSC switch being tested a load resistance of 0.1 mohm will allow about 80% of the total current to be switched to the load while a 3 mohm load resistance will allow only 30% of the total current to be switched to the load. The switchable load current will increase, when all the other

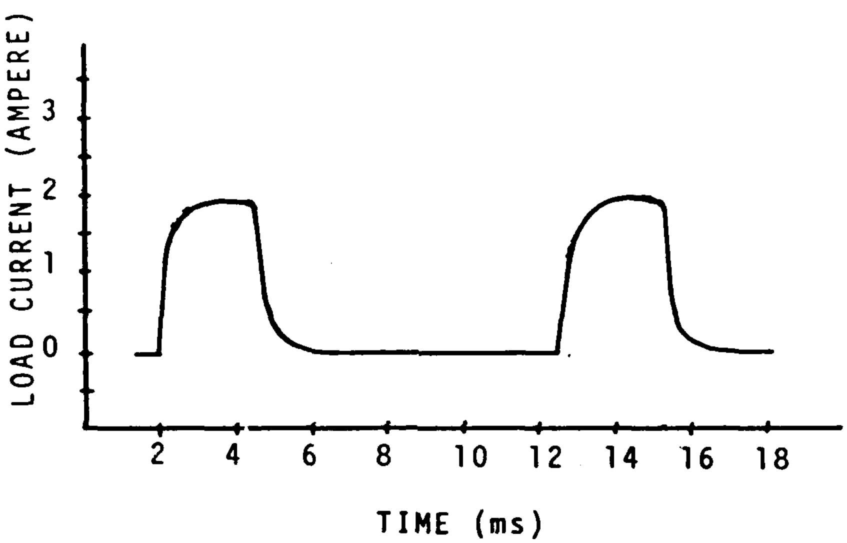

Fig. 4. Waveform of the current that is switched to the load resistor by the applied magnetic pulses.

parameters are kept the same, if the HTSC bar is made longer or an HTSC with higher normal state resistance is used since the I-V curves for the HTSC switch will shift upward with increasing normal state resistance for the HTSC. When a magnetic pulse or pulse train is applied to the HTSC switch the waveform is determined by the magnetic pulse as well as the I-V characteristics shown in Fig.3. A typical oscilloscope trace of the load current detected by a current probe is shown in Fig.4. The rise-time of the load current is determined by the time it takes for the magnetic field to increase to about 100 gauss. Therefore, a fast rising magnetic field will result in a rapid switching operation. The recovery of the HTSC switch after the magnetic field decreases to zero is fast enough for the operation of the switch at 1 kHz. Shorter fall-time for the load current waveform is expected if a magnetic pulse with fall-time shorter than the one used in this experiment is applied.

In summary, a jitter free, repetitive HTSC opening switch has been demonstrated and studied. This switch is very useful as an opening switch for low resistance loads. The "weak coupling" effect for superconducting grains in ceramic HTSC has been applied for the control of the opening switch with pulses of magnetic field around 100 gauss. Operation of this switch at a rep-rate up to 1 kHz has been demonstrated. Further studies are being conducted for the exploration of the optimal performance of this class of HTSC opening switches.

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III. Microwave Controlled High Tc Superconductor Opening Switch

Microwave quenching of ceramic superconductor $YBa_2Cu_3O_{7-x}$ from superconducting to normal state (resistivity ~ 10^{-3} ohm-cm) is studied. An opening switch based on this technique has been demonstrated. The operation of this very promising class of opening switch will be discussed.

The absorption of millimeter-wave power by high Tc superconductor $YBa_2Cu_3O_{7-x}$ [1] has been reported[2]. The surface resistance of superconductor thick films have also been measured in the frequency range 7.0-16.7 GHz[3]. The power dissipation in the superconductor caused by microwave can be explained by the surface resistance of the superconductor. When the dissipated power is greater than the rate at which the cooling mechanism can remove the heat from the superconductor, the deterioration of the superconductor will accelerate due to the ohmic heating in the deteriorated layer and the reduction of critical current. We have studied the interaction of microwave power with a current carrying $YBa_2Cu_3O_{7-x}$ superconductor and demonstrated for

current carrying $YBa_2Cu_3O_{7-x}$ superconductor and demonstrated for the first time a microwave controlled opening switch.

$YBa_2Cu_3O_{7-x}$ superconductor is prepared by the solid state sintering process that has been reported previously[4]. A rectangular bar of superconductor with four silver contacts[4] is used as the test switch. A current supplied by a current source flows between the outer two contacts on the superconductor bar with the inner two contacts connected together with a copper wire to form 80 mohm resistor. The test sample is placed inside a liquid nitrogen container that is inserted into a rectangular microwave waveguide as shown in Fig. 5. The power supply of a commercially available microwave oven is used to generate 2.45 GHz microwave pulse trains at 60 Hz repetitive rate with average power up to about 500 watts. This power supply can provide microwave power in a period for about 3 seconds or longer. Although the microwave power output is not very reproducible when it is turned on for only a few seconds, we have been able to demonstrate the operation of an opening switch controlled by microwave quenching of the superconductor using this simple setup.

As shown in Fig. 6, a Tektronix A6303 current probe is used to measure the current that flows through the load resistor connected between the inner two contacts on the superconductor bar. Three amperes of current flows through the outer two contacts on the superconductor switch. When the switch is superconducting, there is no current flowing through the load resistor because the switch has zero resistance. When the microwave power is applied on the switch, the absorbed power causes the switch to become nonsuperconducting. The resistive

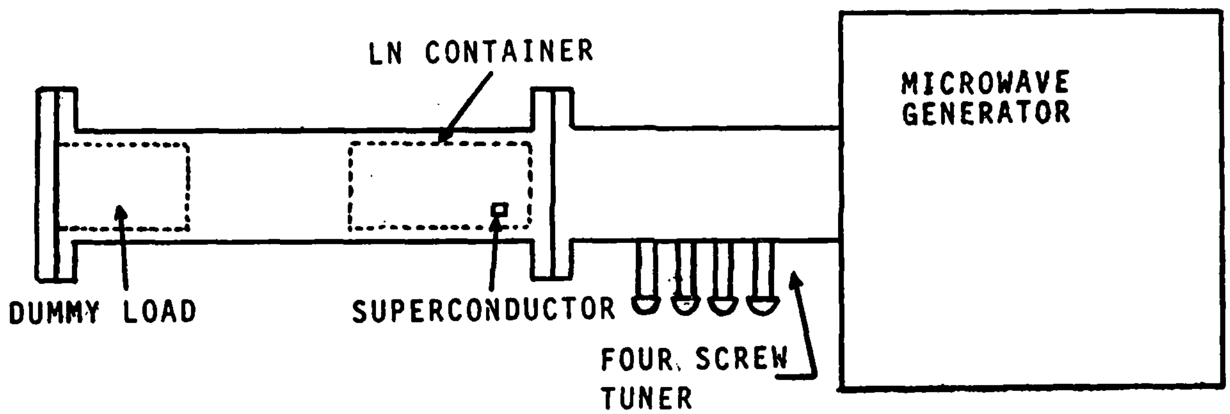

Fig. 5. Schematic diagram of the experimental apparatus used for microwave controlled high Tc superconductor opening switch study.

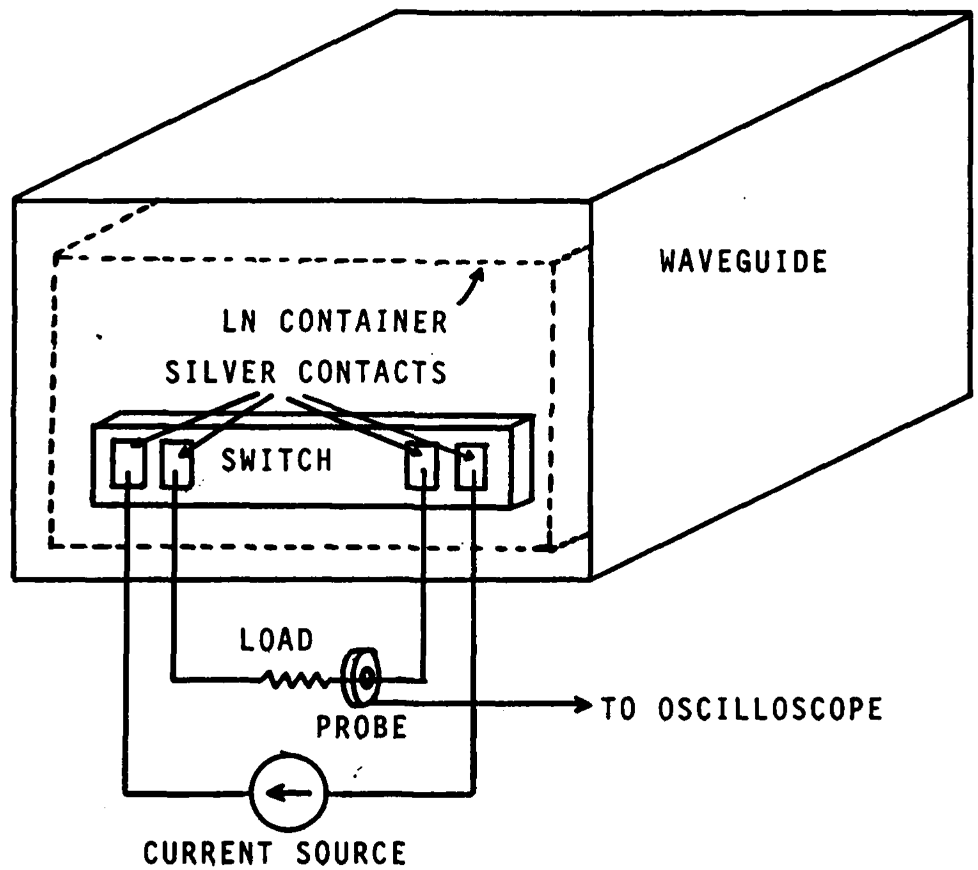

Fig. 6. Circuit diagram of the microwave controlled high Tc superconductor opening switch system.

switch is thus connected in parallel with a 80 mohm low resistance load resistor. This causes current flow to divide between the switch and the load. The amount of current that can be switched to the load is determined by the resistance of the load as well as the resistance of the switch between the inner two contacts when the superconductor is quenched by the applied microwave power. Shown in Fig. 7 is a typical current pulse that flows through the load when microwave power is applied to the switch. About 20% of the total current is switched to the 80 mohm load in this case. The rise-time for this current pulse is about 100 ms while the fall-time is longer than one second. The slow rising waveform is partially caused by the gradually increasing output power level within the first few half-cycles of the microwave power generated by the simple microwave oven power supply. The rise-time is expected to be much shorter if a microwave pulse with shorter rise-time is applied to a thinner superconductor sample. The slow recovery of the superconductivity as shown in the slow decay of load current pulse after the microwave quenching also shows that the temperature of the superconductor is raised well above the superconductivity transition temperature by the microwave power. In order to prevent the wires connecting the switch inside the waveguide to external instruments from arcing due to the microwave power, an insulating paint, NO-ARC, is applied to the superconductor. This paint has low thermal conductivity and is at least partially responsible for the slow cooling and therefore recovery of the superconductivity of the switch after being quenched by the microwave power although the switch is immersed in liquid nitrogen during the experiment.

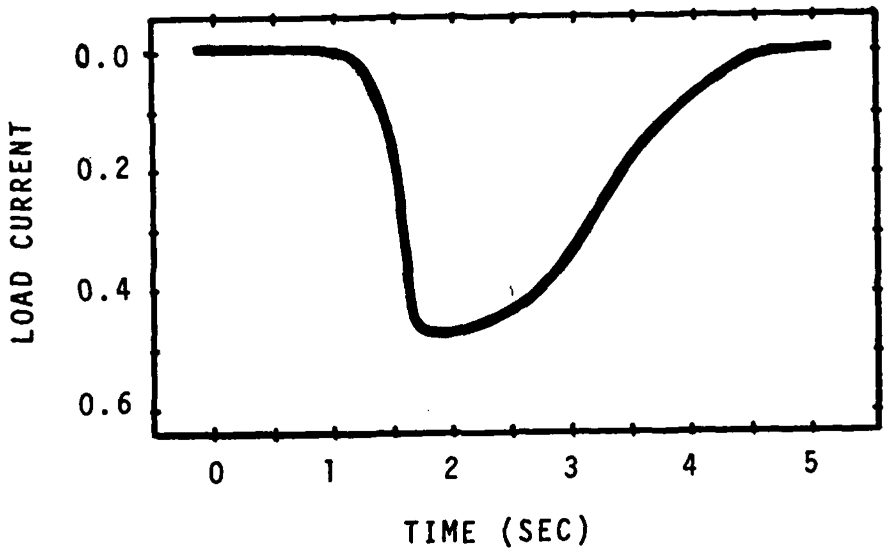

Fig. 7. A typical current waveform for the current switched by the microwave power to the load resistor.

In summary, a microwave controlled high Tc superconductor opening switch has been demonstrated. Further studies of this class of opening switch and the understanding of interactions between superconductors and microwave are being conducted using a microwave generator with better controllability and reproducibility.

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IV. Pulsed Current Controlled High Tc Superconductor Switch

When a current pulse is applied to the outer two contacts in the superconductor bar shown in Fig. 1, the total current flowing through the superconductor can be made to exceed the superconductor critical current density for the given switch dimensions. The extra current flowing through the superconductor makes it become resistive and therefore causes part of the current to flow through the inner two contacts in the superconductor and the load resistor. Once the current flowing through the superconductor decreases due to the by-pass of the current to the load resistor the resistance of the

superconductor switch decreases too. This will lead to a balance between the switch resistance and the amount of current being switched to the load of given resistance. For silver contacts with negligible contact resistance and the load with very small resistance, approximately the amount of current that exceeds the critical current of the switch will flow through the load. When the controlling current pulse is terminated, the load current also decreases to zero. In this mode of operation, there is no current or power gain for the switch. The operation of high Tc superconductor switches with low or medium current densities is in this mode and is therefore not useful.

If a current pulse exceeding the critical current of the switch made of superconductors of very high critical current densities is applied to control the switch, the power dissipation that occurs in the switch during the quenched state of the superconductor can raise the temperature of the switch. Therefore, the switch will stay open for a period of time until it is cooled down to below the superconductor transition temperature again. When the superconductor switch is operating in this mode, it is possible to use a short current pulse to control the switch for switching current of longer period to the load. This will provide at least a power gain to the switch operation, i.e. it used less power to control the amount of power to be switched to the load. Due to the lack of superconductors with high enough critical current density during the six-month period we have not been able to demonstrate this mode of switch operation. Further research and development will be conducted to explore this possibility.

V. Conclusions

Three approaches have been explored to quench high Tc superconductors for the application as opening switches. Among these three approaches, pulsed current quenching is not applicable to superconductors with low critical current density; magnetic field quenching is fast but requires fast magnetic field pulse generator; and microwave quenching is mainly a thermal process at least under our experimental conditions and therefore is relatively slow. Since superconductors with high critical current densities will also require high magnetic fields for quenching, microwave or pulsed current quenching might become superior approaches for the operation of opening switches made of superconductors with very high critical current densities. It is also possible to combine these three and other possible quenching approaches to give better switch performance. Further research is needed to explore this parameter space.

This project has been conducted by Dr. Y. Tzeng with significant contributions made by co-investigators Dr. C. Wu and Dr. T. Roppel and a number of graduate and undergraduate students. The admistrative assistance provided by Dr. R. Askew is highly appreciated.